Assessment of the National Transonic Facility for Laminar Flow Testing

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A transonic wing, designed to accentuate key transition physics, is tested at cryogenic conditions at the National Transonic Facility at NASA Langley. The collaborative test between Boeing and NASA is aimed at assessing the facility for high-Reynolds number testing of configurations with significant regions of laminar flow. The test shows a unit Reynolds number upper limit of 26 M/ft for achieving 'natural' transition. At higher Reynolds numbers turbulent wedges emanating from the leading edge 'bypass' the natural transition process and destroy the laminar flow. At lower Reynolds numbers, the transition location is well correlated with the Tollmien-Schlichting-wave N-factor. The low-Reynolds number results suggest that the flow quality is acceptable for laminar flow testing if the loss of laminar flow due to bypass transition can be avoided.

I. Introduction

HIGH Reynolds number ground-based testing poses significant challenges for studying configurations that exhibit large regions of laminar flow. In the flight regime, which is being modeled in the ground test, the transition to turbulence occurs as a result of naturally growing instabilities. The initial levels for the instabilities, and their relative significance, are strongly dependent on the disturbance environment. Thus, for a ground-based test to be representative of flight, it is necessary that the model characteristics and the wind-tunnel flow quality are sufficiently good to ensure that the observed transition locations are characteristic of flight.

The need for good wind-tunnel flow quality has lead to the development of guidelines and assessment methods for high Reynolds number facilities (see for example [1-3]). The objective of these guidelines is to ensure the proper balance between traveling cross-flow (TCF) and stationary cross-flow (SCF) instabilities, and between SCF and Tollmien-Schlichting (TS) instabilities. A further objective is to ensure that the extent of laminar flow – as expressed by an amplification N-factor – is representative of flight. A detailed assessment of a wind-tunnel facility requires the measurement of both the acoustic and vortical content of the free-stream fluctuations, including spectral information. However, a single turbulence measure Tu often provides a good indicator of the flow quality and of the suitability for laminar-flow testing. An alternative to the measurement of free-stream fluctuations is to directly measure the transition location at carefully-controlled flow conditions. This provides direct information about the

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parameter of interests (transition location), and also enables an estimate of the flow quality using N-factor correlations.

The current study is a joint effort of Boeing and NASA to assess the suitability of the National Transonic Facility (NTF) for testing of configurations with significant extents of laminar flow. The approach taken is to directly measure transition location for well-known flow conditions. The transition location is measured using Temperature Sensitive Paint (TSP). The test model is designed to exhibit both TS and SCF transition over different parts of the wing at different Reynolds numbers. The leading edge is initially highly polished to ensure that SCF does not universally overpower TS waves at higher unit Reynolds numbers.

II. Aerodynamic Wing Design

The wind-tunnel model (shown in figure 1) is designed specifically to assess the NTF regarding potential extents of laminar flow. The wing is designed to achieve laminar flow with a mix of TS and SCF transition at Reynolds numbers between 11 – 22 million (22M/ft – 44M/ft) at a Mach number of 0.8; Re is based on the mean aerodynamic chord length. The leading-edge sweep is 25 degrees. The Boeing CFD code (Tranair [4-6]) is used to design the wing; this code is based on non-linear full potential equations with fully coupled integral boundary layer. A stability code based on compressible linear stability theory (e.g. [7, 8]) is used to calculate the growth of instabilities and predict the transition location.

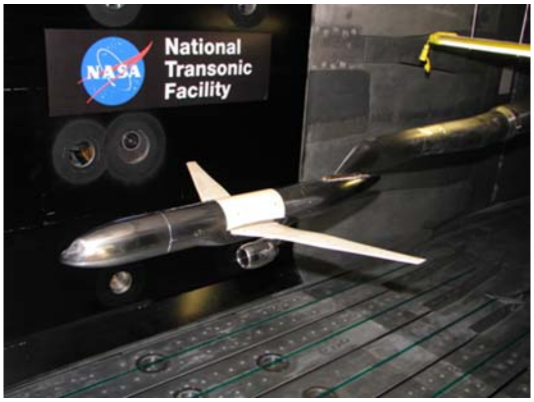


Figure 1 Wind Tunnel Model at NTF

In practice, the boundary layer can undergo transition due to growth of instabilities or from some form of bypass transition. Sources of bypass on a swept wing include: attachment-line contamination, separation, high free-stream turbulence and large surface roughness. So, the first requirement in assessing the facility is that no facility-unique bypass mechanism dictates the transition process. Instability based transition results from the growth of instabilities from low-level finite-amplitude disturbances. At moderately-low levels of free-stream turbulence, the dominant instabilities for a swept wing are TS waves and SCF instabilities [9]. At higher levels of free-stream turbulence, TCF instabilities become more important – this may influence the transition location in a manner inconsistent with flight. Also, at higher levels of free-stream turbulence (more specifically free-stream acoustics) TS waves may start with higher initial values, thus requiring less amplification (smaller N-factors) before initiating transition.

For predicting and interpreting transition, separate N-factors are calculated for each of the instabilities. For the model around the nominal test conditions, the values for the target SCF N-factor range between 4 and 7. Meanwhile, the TS N-factors range between 4 and 8. The bias toward lower N-factors anticipates potential knock-downs due to flow quality. SCF transition is expected on the inboard part of the wing, and TS transition on the outboard part of the wing – with the zone of SCF transition increasing with Re. Moderate monotonic growths of SCF and TS N-factor envelopes were pursued to provide a good N-factor correlation with wind tunnel data. Figure

2 shows an example wing-cut Cp distribution with its SCF N-factor. Figure 3 shows an example of a different wing-cut Cp distribution with its TS N-factor.

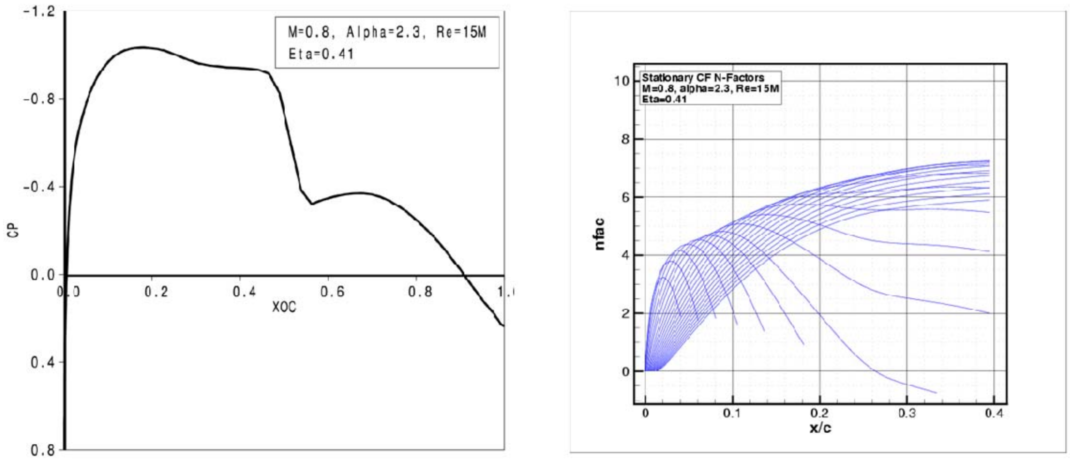


Figure 2 Examples of Pressure-Coefficient Distribution and stationary CF N-factors at 41% span

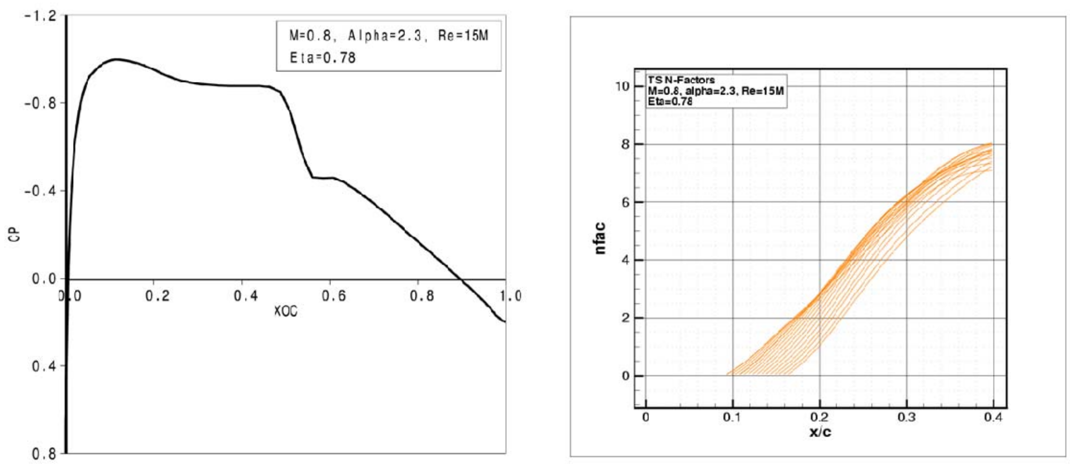


Figure 3 Example of Pressure-Coefficient Distribution and TS N-factors at 78% span

III. Wind-Tunnel Model and Transition Detection

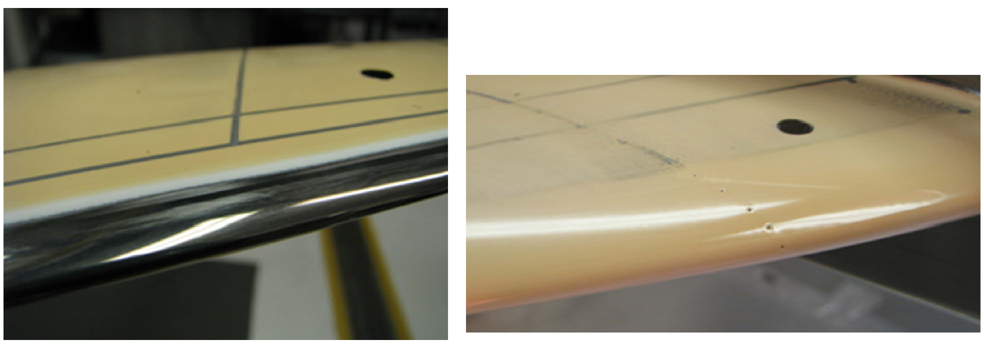
The wind tunnel model is a full model with a scale of 0.0406. It has a wing span of 5 ft and a mean aerodynamic chord length of 0.51 ft. The left wing is free of pressure ports in the leading edge region to avoid premature transition (forward of 30% chord length on the upper surface to forward of 7% chord length on the lower surface). The right wing has pressure ports in the leading edge region to provide information on the leading-edge pressure architecture. It also has pressure ports aft of the leading-edge region to provide comparison between the left and the right wings. Both left and right wings were designed to have clean upper surfaces with no part seams.

Temperature Sensitive Paint (TSP) is used in detecting the transition location. It utilizes the difference in heat transfer between turbulent and laminar boundary layers. By varying the tunnel total temperature, the higher heat transfer in the turbulent boundary layer creates a measurable difference in surface temperature relative to the laminar boundary layer. This variation in surface temperature enables transition visualization using TSP [10]. During a typical TSP session, the tunnel total temperature is varied by about 20 - 30^{o}F.

TSP utilizes a polymer-based paint in which luminescent molecules are immobilized [11]. TSP is analogous to the Pressure Sensitive Paint (PSP) method, except that in the case of TSP, the binder is chosen so that it is impermeable to oxygen. The luminescent molecules are typically chosen so that their quantum yield decreases with increasing temperature, otherwise known as thermal quenching. The relationship between the luminescence and the absolute temperature generally follows Arrhenius behavior over a certain range, which is molecule dependent. Thus, a judicious selection of the luminophore in a TSP can lead to formulations that are temperature sensitive from cryogenic to 392°F [10-15].

For cryogenic testing, the binder must be able to withstand not only the extreme temperatures experienced during testing, but also must adhere to the highly polished surface that is required for the model. In addition, to have a minimal effect on the flow, the paint must be able to be applied thinly and evenly, and have very low surface roughness. For this work, a polyurethane binder material was chosen because of its temperature durability. To enhance its adhesion to the model, the polyurethane binder was applied over a primer using traditional painting techniques. After suitable handwork and polishing, the thickness of the TSP was approximately 3 mils (76 µm) with a roughness of 20 µinches (0.5 µm) or less. The luminescent molecule ruthenium terpyridine [Ru(trpy)] was immobilized in the polyurethane binder to visualize the temperature changes on the model surface. This molecule displays temperature sensitivity from -274°F to -58°F, and has previously been used for cryogenic TSP testing [10,13].

Figure 4 shows two TSP applications to the wind-tunnel model used in the current study. The first is an unpainted leading edge with TSP applied at 8% chord (Figure 4a). The paint line is polished and feathered to avoid creating a paint step. The second application has TSP applied to the entire wing. The leading edge is then polished and waxed to get the best possible surface finish.



a) b)

Figure 4 TSP applications a) unpainted LE, TSP polished and feathered to the LE b) painted LE

IV. Transition Results

Temperature Sensitive Paint (TSP) provides excellent images for detecting the transition location. Figure 5 shows a TSP image for the upper surface of the left wing at Re 7M – flow is from top to bottom in the image. Negative free-stream temperature gradient is used during transition detection. In Figure 5 and the other images shown in the paper, lighter regions signify laminar flow and darker regions, turbulent flow. The downstream limit of laminar flow on the outboard wing is the result of the shock. The triangular wedges are the result of some form of surface contamination near the leading edge of the wing.

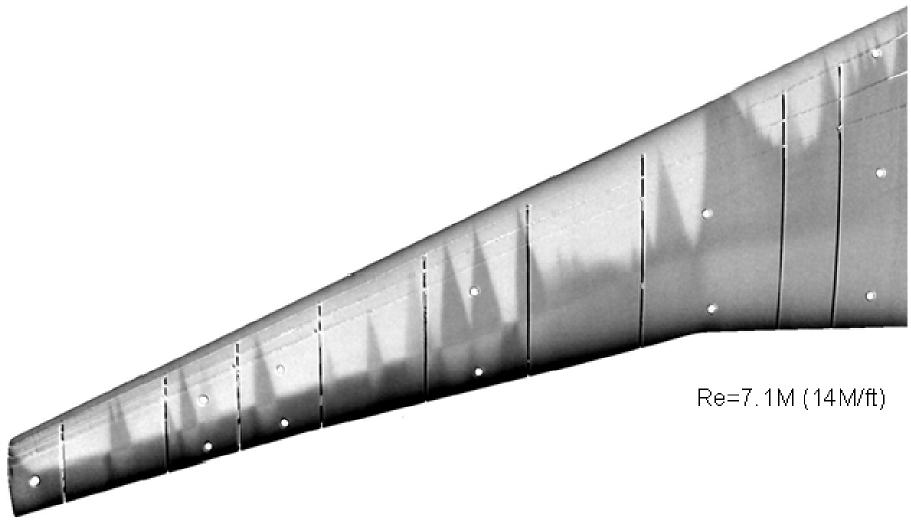


Figure 5 Transition result at low Reynolds number

Attaining a useful level of laminar flow on a full model at high Reynolds number is difficult due to the extremely-thin boundary layer at high unit Reynolds numbers. Having pristine surface quality (with minimal steps and minimal surface roughness) is fundamental to avoiding bypass transition and achieving laminar flow as predicted.

The impact of different surface imperfections (related to TSP) on transition at Reynolds number of approximately 9M is shown in Figure 6. The wing leading edge is initially unpainted with TSP applied at 8% of chord, Figure 6a. A moderate amount of feathering is done to the model. A significant number of turbulent wedges are detected and a clear transition location can not be seen. By feathering the TSP paint line to approximately 20% chord (yielding roughly a 1:0.004" slope at chord length of 0.51 ft), some bypass-transition wedges are eliminated and regions with a clear transition location are detected, Figure 6b. Figure 6c shows the model with the leading edge painted. Painting the leading edge removes the effect of step on the transition location and is helpful for investigating potential sources for the turbulent wedges. With the painted leading edge, the number of turbulent wedges increases, which makes it difficult to assess the natural transition location at this Reynolds number. At lower Reynolds numbers (not shown), painting the LE reduces the turbulent wedges and moves the natural-transition line downstream. The painted model, waxed and polished, is shown in Figure 6d. The waxed model reduces the number of turbulent wedges and moves the nominal transition location downstream compared to Figure 6c. This painted and waxed model provides the most useful transition data. These figures show that the transition location is clearly impacted by the step and the surface roughness. Removing the step, by painting the leading edge, results in a modest downstream shift in transition location. Painting the leading edge, however, introduces surface roughness, which is managed by waxing and polishing the model.

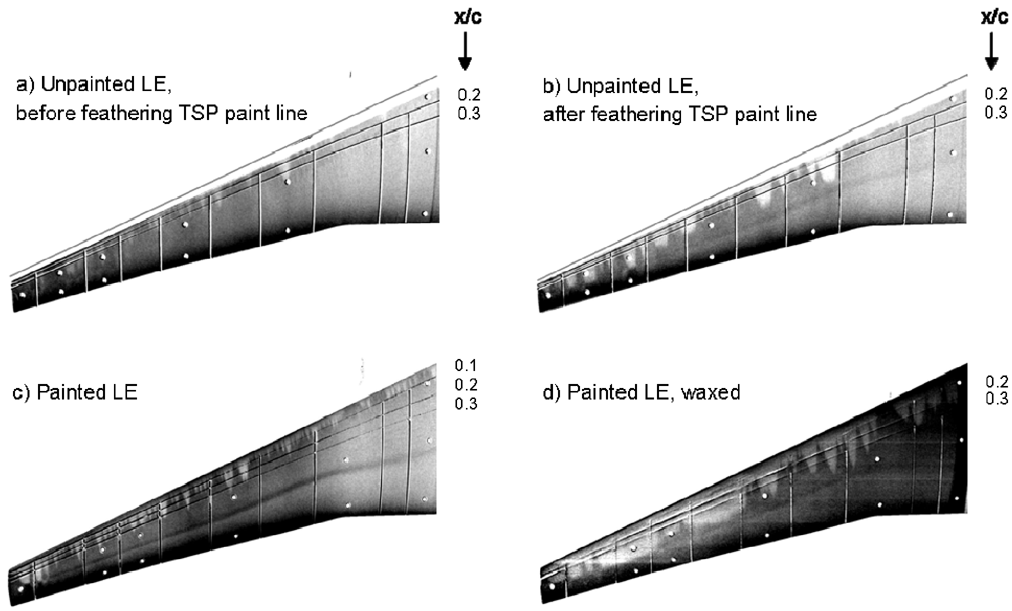


Figure 6   Transition movement with variation in surface finish at M=0.8, alpha=2.3, Re~9M

Figure 7 shows the variation of laminar flow with Reynolds number. As the Reynolds number increases, the transition front moves upstream as expected. More turbulent wedges also form and coalesce at higher Reynolds number, which suggests surface roughness has become unacceptably high (see section V.) The higher Reynolds number images show similar results to Figure 6, which are at Reynolds number of 9M, but with known surface roughness influences.

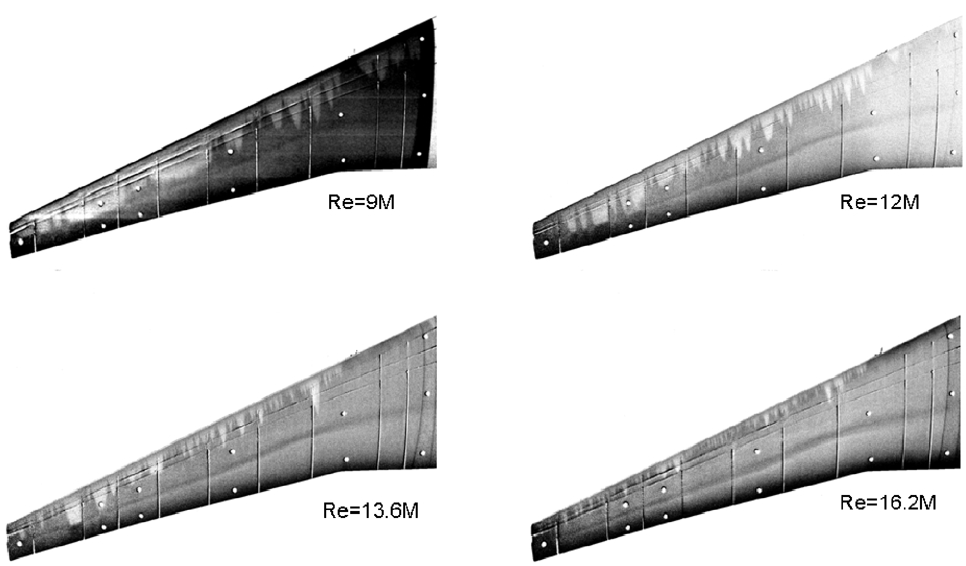


Figure 7   Transition movement with Reynolds number at M=0.8 alpha=2.3 painted and waxed LE

V. Limits for Achieving Laminar Flow

The highest Reynolds number where laminar flow was detected with painted and waxed LE was about 16M. However due to the large number of turbulent wedges formed at this Reynolds number, no useful data could be gathered. At Reynolds number of 13.6M, data was able to be used in small areas of the wing. Figure 8 shows the TSP image at Reynolds number of 16.2M and 13.6M.

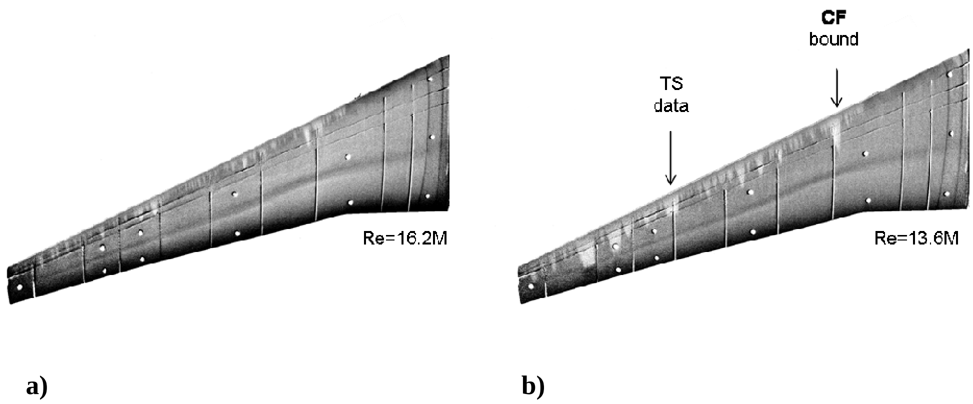


Figure 8 Highest Reynolds number at M=0.8, α=2.3^o with:
a) detected laminar flow, Re_{MAC}=16.2M (31.7M/ft) b) useful data, Re_{MAC}=13.6M (26.6 M/ft)

The results of the NTF are compared to results of the European Transonic Wind tunnel [ETW] provided in Ref. 16 (shown in Figure 9.) The NTF test images are for Mach of 0.8 and angle of attack of 2.3 degrees. The ETW results are for a DLR F4 model at Mach of 0.785 and angle of attack of -0.87 degree. Both tests result in comparable extents of laminar flow. NTF unit Reynolds number are about 2 M/ft higher than the ETW unit Reynolds numbers for the cases shown. Both tests show an increased loss of laminar flow at higher Reynolds numbers due to turbulent wedges. However, the NTF results generally show more wedges than the ETW results.

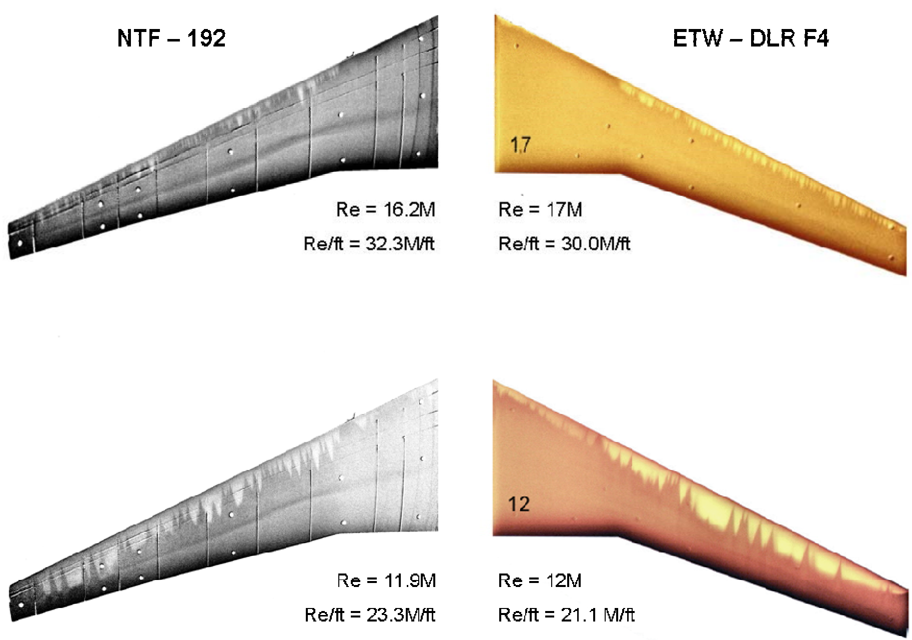


Figure 9 Comparison to ETW [16]

The difficulty in getting laminar flow anywhere close to predicted at Reynolds numbers higher than 16M suggests that some form of bypass transition is responsible. The possibilities of having contamination from the attachment-line, from high free-stream turbulence and from large surface roughness are assessed. Attachment-line contamination at Reynolds number of 16M is easily ruled out. TSP images in Figure 8a shows that at this Reynolds number there are some regions of laminar flow along the entire wing, with turbulent wedges emanating from the leading edge. This is inconsistent with attachment line contamination. For this wing, up to Reynolds number of 22M, $\overline{R}$ varies smoothly along the leading edge and stays below 245 for the outboard 70% of the wing. The attachment line is expected to be laminar for $\overline{R} \leq 245$ [17].

In the case of high vortical content in the free-stream fluctuations, traveling cross flow (TCF) can become the dominant form of cross-flow instability. At Reynolds number of 15M, the SCF maximum N-factor is below 5.5 over the outboard half of the wing. Sectional comparisons between SCF and TCF N-factors show a difference of about one. With these modest N-factor values, traveling cross flow is not likely to be the source of loss in laminar flow. Another reason to rule out TCF is that for a short timeframe, of several seconds, the wedges do not move but rather appear fixed to some form of surface irregularity. Thus, large surface roughness is suspected to be the source for the loss of laminar flow.

Figure 10 shows the repeatability of laminar flow at Reynolds number of 7M. The images are taken within a five-hour timeframe with no tunnel entry. In between time t1, t2, and t3 various test conditions were run: varying Reynolds number, Mach, and angle of attack. Between time t1 and t2, there was an hour period where the tunnel was at rest and brought to a slightly higher Temperature. With the model untouched, between time t1, t2, and t3, some wedges were formed and some wedges disappeared. The variability is shown with arrows. These runs were taken with the model leading edge unpainted. The same finding is found with painted and waxed leading edge. The variability over time suggests that there is unknown surface roughness that changes with time. There is evidence that frost was present behind the nacelle and nose trip dots during several runs. Frost on the wing leading edges could not be detected but it was thought that it might be present as well. Oil streaks on the wing upper and lower surfaces were also detected during model check at the end of some runs. Based on this evidence, and the variability of turbulent wedges with time, the presence of oil and/or frost is suspected to be the source of loss in laminar flow.

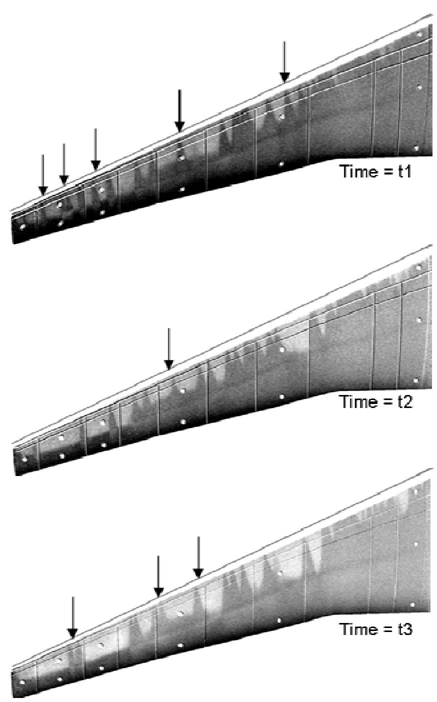


Figure 10 Variability of transition over time with unpainted LE at M=0.8, alpha=2.3, and Re=7M

VI. Assessment of Flow Quality

The TS wave transition N-factors are correlated with data gathered at lower Reynolds numbers where clear transition fronts could be observed. Figures 11 and 12 show TSP images compared to the predicted transition with TS N-factor of 4 as the worst-case scenario (where the turbulence level is high) and with TS N-factor of 8 as the best-case scenario (where the turbulence level is low). Transition front data from TSP images are compared to the prediction as shown by the symbols. At spanwise locations where the natural transition location is confused by turbulent wedges, the transition front is shown as a dashed line on the TSP images and as open symbols on the N-factor plot. Detailed comparisons between wind-tunnel data and predictions consistently show a TS N-factor of about 6.

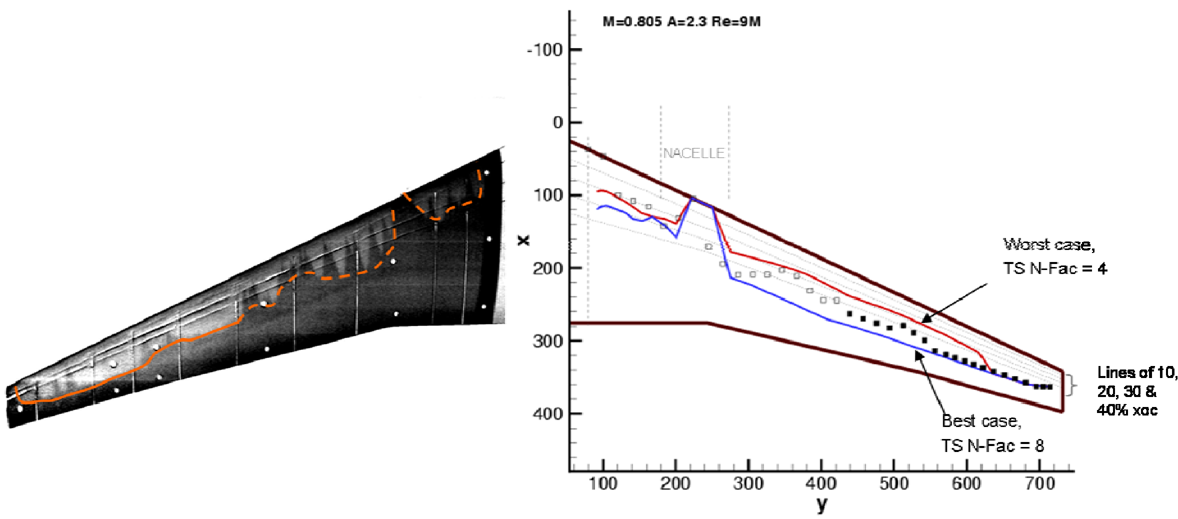


Figure 11 Comparison between wind tunnel data and numerical predictions at Reynolds number = 9M

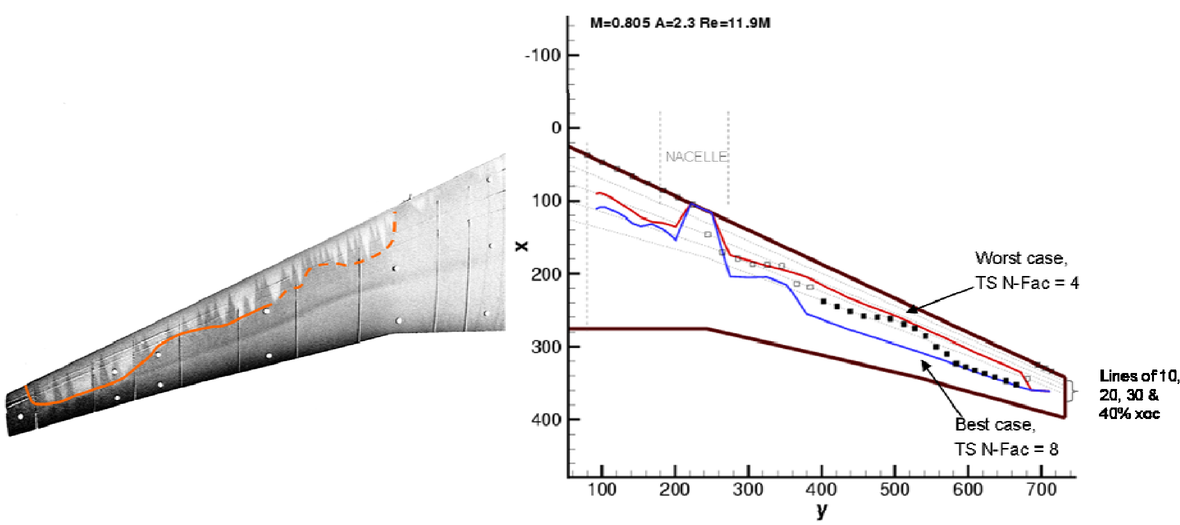


Figure 12 Comparison between wind tunnel data and numerical predictions at Reynolds number = 12M

The variable TS N-factor correlation to the free-stream turbulence proposed by Mack [8] is used in estimating the effective turbulence level of the facility. This correlation was initially developed by finding a fit to the observed TS N-factors and the turbulence intensity Tu, based on the flat-plate transition data presented by Dryden [18]. The fit gives the TS wave N-factor expression

$$N_{TS} = -8.43 - 2.4 \ln (Tu) \quad . \tag{1}$$

This empirical relation matches observation reasonably well for 0.1%>Tu>1% [9]. Using equation (1), TS wave N-factor of 6 implies a turbulence level of approximately 0.24%. This is a reasonable Tu level for a transonic wind tunnel, and is acceptable for configuration-type testing.

The cross-flow N-factor is not able to be correlated with data due to the Reynolds number limit. At Re = 7 M, transition is uniformly due to TS waves. At Re=9 M and 12 M, there are regions inboard and slightly outboard of the nacelle that are likely transitioning due to SCF. However, there are too many turbulent wedges in those regions so that useful data can not be gathered.

VII. Conclusions

The TSP proved to be a very effective means of detecting transition in the cryogenic environment. Results for an unpainted and highly-polished leading edge showed slightly less laminar flow compared to a painted and waxed leading edge. This is attributed to the paint edge, even though the paint edge is blended over several percent of the chord.

The extent of laminar flow is limited at higher Reynolds numbers due to the prevalence of turbulent wedges emanating from the leading edge of the wing. The maximum Reynolds number where laminar flow could be detected is 16 million (31M/ft). Any assessment of a natural-transition boundary is limited to Reynolds numbers below 13 million (25.4 M/ft). The turbulent wedges are attributed to 'surface perturbations' or 'roughness' on the leading edge of the wing. However, the turbulent-wedge locations (and thus the inferred 'roughness') changed over time – as flow conditions were varied but in the absence of any contact with the model. This leads to the conclusion that the loss of laminar flow is likely the result of frost or oil on the leading edge.

At lower Reynolds numbers, where natural transition could be observed, the transition location is well correlated with a TS-wave N-factor of 6. Based on this N-factor and the correlation of Mack [8], the effective turbulence intensity is estimated to be about 0.24%. This is inline with other transonic wind tunnels, and is sufficient to allow for laminar-flow testing. The limitation of only observing natural transition at lower Reynolds numbers inhibited an evaluation of the transition characteristics resulting from cross-flow instability.

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